

## CHARACTERIZATION OF DIFFUSION BONDS USING AN ACOUSTIC MICROSCOPE

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### INTRODUCTION

Solid state bonding is now being used in aircraft fabrication. As a result of this, various groups have considered the destructive examination of such bonds and categorized them in terms of characteristics seen in the examination of micrographic sections [1,2]. A range of studies which employ ultrasonic non-destructive techniques for bond-line characterization have also been undertaken [1,3,4].

A procedure for estimating the bond-line response for compression wave (C-scan) imaging was presented previously [3]. This involves the determination of bond-line reflection and transmission coefficients using leaky Rayleigh wave imaging and gives coefficients that are independent of the system used and sample plate thickness. These coefficients can then be used to estimate the compression wave bond-line response for the same material.

This study has considered the characterization of titanium-titanium and two forms of aluminum-lithium diffusion bonding applied to sheet material typically 3 mm thick. A Pulsed Digital Reflection Acoustic Microscope (PDRAM) (25-100 MHz) has been used to characterize the diffusion bond-lines between sheet material [4] and this work is an extension of an earlier study [3].

### ACOUSTIC MEASUREMENT CONFIGURATIONS

A PDRAM operating with various 50 MHz transducers is used to characterize the diffusion bond-lines between sheets of titanium. This system has also been employed in various materials characterization

studies, and it has been described elsewhere [3,4].

The PDRAM system is used in two different imaging configurations.

### Leaky Rayleigh Wave Imaging

For the ultrasonic characterization of the bond-line seen in optical micrograph examination, a spherically focused compression wave transducer is defocused as shown in Fig 1(a). This causes leaky Rayleigh waves to be generated in the surface of the sample [3,4,5,6]. The leaky Rayleigh wave component is then isolated and measurements of signal level made using the gated peak detector in the PDRAM. The resulting data is used to give images and also both  $V(x)$  and  $V(y)$  curves, measured across and along the bond-line respectively.

The  $V(x)$  curve has previously been used for the characterization of several types of surface breaking features [5,6,7,8] and it has been shown to enable the determination of both transmission and reflection coefficient data [5] for surface breaking features.

For an acoustic microscope used with a cylindrical/line focus lens, it has been shown [8] that the relationship between the output of the transducer  $V(x,z)$  and the elastic material properties are given by:

$$V(x,z) = \int_{-k_0}^{k_0} \int_{-k_0}^{k_0} \exp[i(k_z' - k_z)z] L_1(k_x') L_2(k_x) S(k_x, k_x') \exp[i(k_x' - k_x)x] dk_x dk_x', \quad (1)$$

and

$$S(k_x, k_x') = \left[ R_0(k_x) + \frac{i4\alpha k_p}{k_x^2 - k_p^2} \right] \delta(k_x - k_x') + \frac{2\alpha}{\pi} \left[ \frac{(T - R - 1)k_x k_x' + (T + R - 1)k_p^2}{(k_x^2 - k_p^2)(k_x'^2 - k_p^2)} \right] \quad (2)$$

where  $k_x$  and  $k_x'$  are the  $x$  components of the incident and scattered plane waves.  $L(k_x)$  and  $L(k_x')$  are the pupil functions for the lens for the incident and scattered plane waves; the crack is taken to be at the origin.  $k_p$  is the Rayleigh pole in the complex  $k_x$  plane.  $\alpha$  describes the strength of coupling of Rayleigh waves to the fluid, and  $R_0$  is the reflectance function minus the Rayleigh pole.

In this formulation (1) the characteristics of the scatterer are included only as the reflection ( $R$ ) and transmission ( $T$ ) coefficients and it has been used to describe various wave/feature interactions including the response for cracks of finite depth, crack closure and different orientations [6]. Line-scans or  $V(x)$  data across cracks have been calculated using a computer program based on this formulation [4,7,8]. This program has been employed to determine the  $V(x)$  response from diffusion bond-lines, and comparison of the resulting data with experimental measurements will be reported in the near future [4].

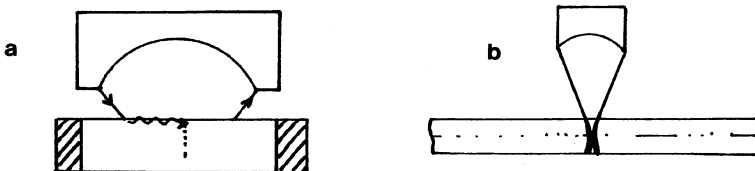


Fig. 1. (a) Leaky Rayleigh wave imaging configuration  
(b) Compression wave imaging configuration

## Compression Wave Imaging

When the acoustic microscope is used with a spherically focused compression wave transducer, it can give C-scans of the bond-line zone as shown in Fig 1(b). The RF, or time-domain, traces are considered, and the system gate is adjusted to measure just the bond-line response. This data is then used to give images and various line-scans from which reflection coefficients are determined [3].

The data obtained in both the acoustic measurement configurations shown in Fig 1 is compared with that obtained from modelling.

## DIFFUSION BOND CHARACTERIZATION

Various groups have reported the use of high frequency ultrasonic C-scan systems to inspect a range of diffusion bonds [1,2,3,4]. In such inspections it has been shown that major voids and inclusions can easily be detected. Some work performed in the range 10-15 MHz [1,2] has also sought to characterize the bond-line between discrete flaws and reflection coefficients have been successfully measured.

### Leaky Rayleigh Wave Measurements

Leaky Rayleigh waves in an acoustic microscope used for surface imaging can be one of the major components in contrast generation and have previously been reported when employed to characterize diffusion bonds [9].

Bond-line samples of titanium-titanium material, that had been classified by optical examination to be either acceptable or unacceptable, provide the bond-line edge-on, which makes it suitable for leaky Rayleigh wave inspection. Images of such samples were obtained at 50 MHz by applying the gate to isolate the leaky Rayleigh wave component reflected by the surface; examples of these are shown as Fig 2. These images show the area around the bond-line and they were obtained using a step size of 50  $\mu\text{m}$ .

In addition to leaky Rayleigh wave images lines-scans were made across and along the bond-line to give  $V(x)$  and  $V(y)$  data respectively. The data for the two cases are shown in Figs 3 and 4.

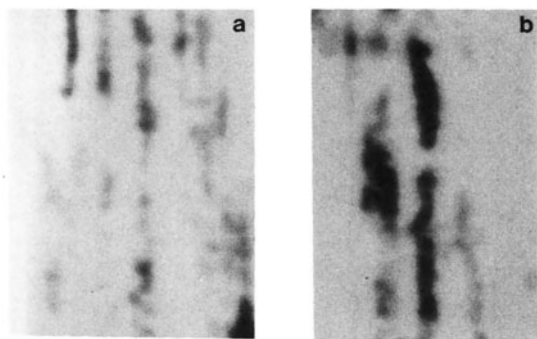


Fig. 2. Leaky Rayleigh wave images of diffusion bonded titanium  
(a) acceptable bond, (b) unacceptable bond.

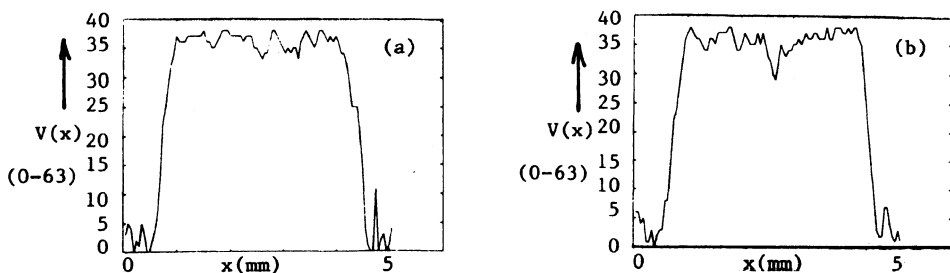


Fig. 3 Leaky Rayleigh wave  $V(x)$  plots for acceptable and unacceptable diffusion bonds, (a) acceptable bond; (b) unacceptable bond.

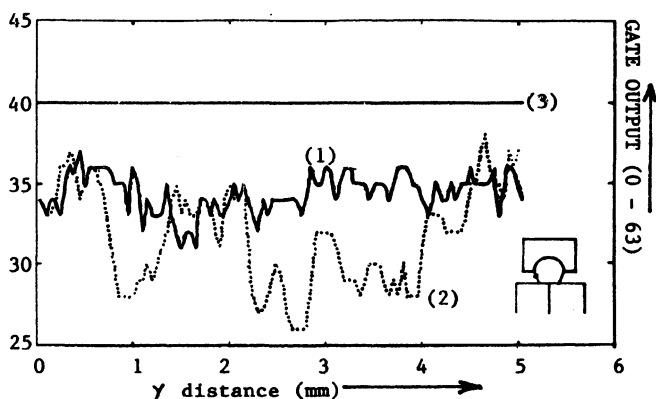


Fig. 4 Leaky Rayleigh wave  $V(y)$  plots for acceptable and unacceptable diffusion bonds, (1) acceptable bond; (2) unacceptable bond; and (3) reference level taken from parent material.

In all the data shown in Figs 2, 3, and 4 it is seen that for an unacceptable bond condition there is a clearly measured difference in signal level compared with that for an acceptable bond. The variability in any bond region is also highly statistical and any single point measurement will not be adequate to characterize a bond. In the experimental  $V(y)$  data given in Fig 4 which is measured along the bond-line the statistical nature of the variability in bond-line and its response to ultrasound is clearly seen. In both acceptable and unacceptable bond-line regions there are areas where the reflection coefficients are the same. The statistics of the  $V(y)$  data shown in Fig 4 are given as Table 1. Two simple parameters which can be used to distinguish between the two classes of bond are the mean and standard deviation for the  $V(x)$  and the  $V(y)$  curves.

Table 1. Statistics for the response obtained from different regions in titanium-titanium diffusion bonds when using leaky Rayleigh wave measurements.

	Acceptable	Unacceptable
Mean	34.43	31.75
Median	35	32
Standard Deviation	1.24	3.10

Using the  $V(x)$  data of the type given in Fig 3 and a method proposed by Weaver et al [5], the transmission and reflection coefficients for the leaky Rayleigh wave response of the bond-line can be determined. The resulting coefficients are given in Table 2. These coefficients have been calculated for the standard deviation range about the mean for each region rather than for single spot values.

Compression Wave Measurements

Using the configuration given as Fig 1(b), compression wave measurements were made at 50 MHz with the gate set to isolate the compression wave component reflected from the bond-line zone. A composite image for a titanium test plate containing three distinct regions of "acceptable", "borderline", and "unacceptable" is shown as Fig 5. The unacceptable region is seen to be significantly brighter than the rest of the plate.

By way of system calibration, the variability of front surface echo was measured on a glass plate, and this gave  $\pm 1$  level variability and also defined the error bands for compression wave measurements.

In addition to compression wave images of the type given as Fig 5, line scan data for both the sample surface and bond-line were recorded. Fig 6 shows the variability for the bond-line in various regions of the plate sample imaged as shown in Fig 5.

To simulated the worst-case of a complete disbond a section of plate was milled to reduce it to the thickness of the single plate material. A 50 MHz center frequency 0.5 inch focal length transducer was focussed on the backwall of this single plate section and the mean backwall response is shown as trace (1) in Fig 6. Also shown in Fig 6 are the response from an acceptable bond-line region which is given as trace (2) and that from an unacceptable region which is given as trace (3).

Table 2. Reflection and transmission coefficient data for titanium-titanium diffusion bonds obtained from leaky Rayleigh wave data.

	Reflection Coefficient	Transmission Coefficient
Acceptable	0.12 - 0.17	0.83 - 0.88
Unacceptable	0.13 - 0.28	0.72 - 0.87

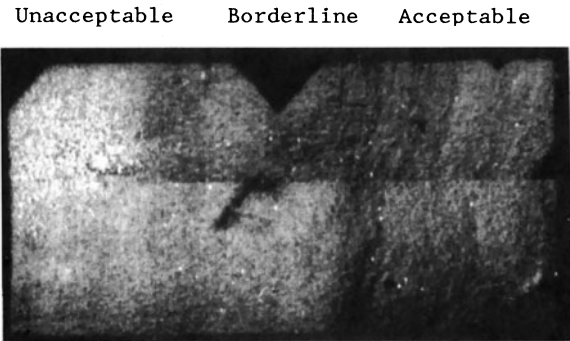


Fig. 5. Compression wave image: diffusion bonded titanium plate.

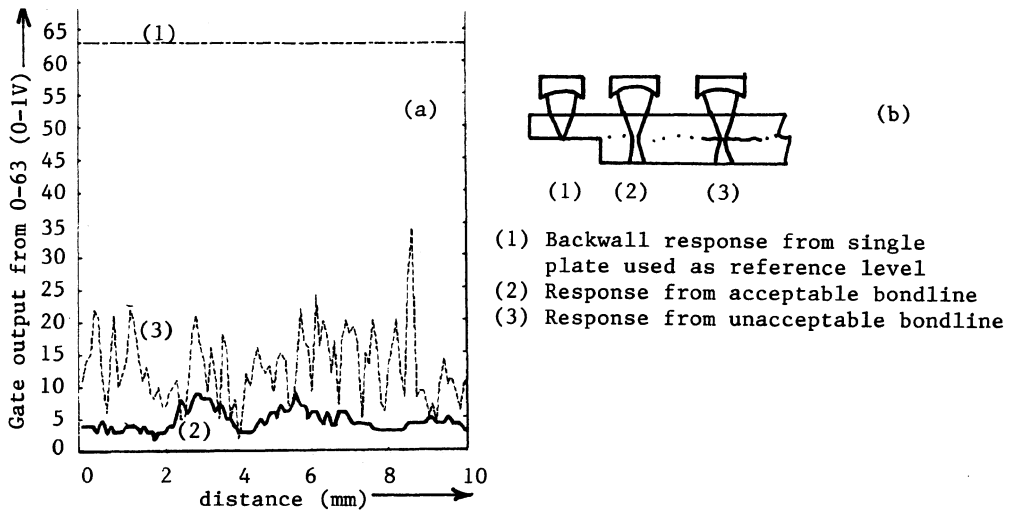


Fig. 6. Bond-line responses from various regions of diffusion bonded titanium plate using compression waves.  
 a. Bond-line response. b. System measurement configurations.

It is seen in Fig 6 that there is a clear differentiation between the response for acceptable and unacceptable bond regions and also that the data for one point will not adequately characterize the bond-line condition. The statistics for the variability in the Rayleigh wave data have been calculated and they are given in Table 3.

Table 3. Statistics of the response obtained from different regions in titanium-titanium diffusion bonds when using compression wave measurements.

	Acceptable	Unacceptable
Mean	34.43	31.75
Median	35	32
Standard deviation	1.24	3.10

The reflection coefficients for the data shown in Fig 6 can be determined [10]. For all three sets of data it is assumed that there is the same incident wave field. The "effective incident field" can be estimated from the data in the step region given that;

$$\text{Incident Field} = \text{Reflected Field} + \text{Transmitted Field}$$

$$I = C_R + C_T \quad (3)$$

If the data for the step region is taken to be that for a perfect titanium-water interface with coefficients  $C_R = 0.8$  and  $C_T = 0.2$ , the effective incident field is then proportional to the back-wall echo corrected for its transmission loss. The bond-line reflection coefficient is then calculated using the voltage measured for the signal reflected by the bond-line divided by the voltage for the "effective incident field". The coefficients for the data shown in Fig 6, are calculated in the same way as that shown in Table 2, these are given as Table 4.

Table 4. Reflection and transmission coefficient data for titanium-titanium diffusion bonds obtained from compression wave data.

	Reflection Coefficient	Transmission Coefficient
Acceptable	0.04 - 0.08	0.96 - 0.92
Unacceptable	0.09 - 0.23	0.77 - 0.91

## DISCUSSION OF RESULTS

The images of acceptable and unacceptable bond-lines shown in Figs. 2 and 5 show clear identification of unacceptable bond regions. A response model was proposed previously [3] which states that for a weak scattering layer the reflection and transmission characteristics are determined by the acoustic impedance contrast and that for such layers both the Rayleigh wave and compression wave reflection characteristics should have similar values. The reflection coefficients obtained using the two ultrasonic bond-line characterization techniques are given in Table 5.

The data given in Table 5 shows that there is good agreement between measurements made with leaky Rayleigh waves and those obtained using compression waves. It is interesting to note that the reflection coefficient values given in Table 5 for regions classified as acceptable and unacceptable cover a similar range to those reported in a study of copper-copper diffusion bonds by Palmer et al [1]. In addition in that work material studies were performed, and it was shown that the variation in bond-line reflection coefficient was related to variation in bond-strength and fractional bonded area.

## CONCLUSIONS

Ultrasonic inspection techniques operating at 50 MHz have been developed which can distinguish between acceptable and unacceptable titanium-titanium diffusion bonds which have been classified by optical examination.

The leaky Rayleigh wave inspection technique when applied to micrographic samples would appear to have the potential to calibrate the response of various types of diffusion bonds and this data can then be related to the response from conventional compression wave (C-scan) inspections made at the same frequency.

The difference in ultrasonic response between an acceptable and an unacceptable diffusion bond is highly statistical. Any practical measurements of ultrasonic bond-line responses will therefore be required to include consideration of the statistics.

Table 5. Reflection coefficient data for titanium-titanium diffusion bonds.

	Leaky Rayleigh Wave Reflection Coefficient	Compression Wave Reflection Coefficient
Acceptable	0.12 - 0.17 $\pm$ 0.03	0.04 - 0.08 $\pm$ 0.03
Unacceptable	0.13 - 0.28 $\pm$ 0.03	0.09 - 0.23 $\pm$ 0.03

## ACKNOWLEDGMENTS

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